Site C Clean Energy Project

Site C Reservoir Tributaries Fish Community and Spawning Monitoring Program (Mon-1b)

Task 2b – Peace River Bull Trout Spawning Assessment – Bull Trout Redds Counts

Construction Year 3 (2017)

Note: This report has been redacted for the protection of Bull Trout (*Salvelinus confluentus*)

Annika Putt, MRM
InStream Fisheries Research Inc.

Daniel Ramos-Espinoza
InStream Fisheries Research Inc.

Doug Braun, PhD
InStream Fisheries Research Inc.

Cole Martin, Assoc Sc Tech
InStream Fisheries Research Inc.

LJ Wilson
InStream Fisheries Research Inc.

Nicholas Burnett, MSc, RPBio
InStream Fisheries Research Inc.

January, 2018

Peace River Bull Trout Spawning Assessment - Bull Trout Redds Counts (Mon-1b, Task 2b)

Annika Putt, Daniel Ramos-Espinoza, Douglas C. Braun, LJ Wilson, Cole Martin, and
Nicholas J. Burnett

Prepared for: BC Hydro – Site C Clean Energy Project

A. Putt*, D. Ramos-Espinoza, D.C. Braun, LJ Wilson, C. Martin, and N.J. Burnett. 2018. Peace River Bull Trout Spawning Assessment - Bull Trout Redds Counts (Mon-1b, Task 2b). Report prepared for BC Hydro – Site C Clean Energy Project – Vancouver, BC. 29 pages + 3 appendices.

*Corresponding author

Executive Summary

This report summarizes the 2017 Bull Trout redd enumeration program in the upper portion of the Halfway River and its tributaries. We conducted four rounds of aerial and ground surveys to visually enumerate Bull Trout redds in five main spawning tributaries; the Chowade River, Cypress Creek, Fiddes Creek, Turnoff Creek, and the Upper Halfway River. We used a Gaussian area-under-the-curve (GAUC) method with maximum likelihood estimation to estimate Bull Trout redd abundance with associated uncertainty. This method incorporates the mean and standard error for the number of fish days, observer efficiency and redd survey life. Data were collected for estimating observer efficiency and redd survey life by marking and re-sighting redds during ground and aerial surveys. Ground observer efficiency was calculated as the proportion of marked redds re-sighted. Aerial observer efficiency was calculated by comparing the expanded number of redds in a ground survey reach to the number observed within the same reach during aerial surveys. Observer efficiency was relatively consistent among tributaries, but aerial observer efficiency varied among surveys (range in mean ground observer efficiency 0.88 to 0.95; range in mean aerial observer efficiency 0.26 to 0.39). Redd survey life was estimated through redd age determination with a mean survey life of 24.2 days and a standard error of 2.30.

The estimated total number of redds was 320 for the Chowade River, 90 for Cypress Creek, 63 for Fiddes Creek, 18 for Turnoff Creek, and 75 for the Upper Halfway River. GAUC estimates were similar in 2016 and 2017 for the Chowade River and Cypress Creek, while estimates declined in 2017 in Turnoff and Fiddes Creeks and increased in the Upper Halfway River. GAUC estimates were within the range of baseline peak count estimates from 2002 to 2012. Redd size varied considerably among and within tributaries (range for all redds: 0.32 to 8.12 m^2). We examine the variation in redd distribution and abundance estimates for 2016 and 2017, and discuss the implications of survey life and observer efficiency estimates between the two years.

Acknowledgements

The Site C Peace River Bull Trout Spawning Assessment is funded by BC Hydro's Site C Clean Energy Project. We would like to thank Brent Mossop and Dave Hunter at BC Hydro and Kevin Rodgers, Jonah Renford, Dieter Mark, and all the support staff at Canadian Helicopters for making our flights safe and effective. Thanks to Josh Korman for valuable comments and discussions on the study.

Table of Contents

List of Figures

List of Tables

1 Project Background

BC Hydro developed the Site C Fisheries and Aquatic Habitat Monitoring and Follow-up Program (FAHMFP) in accordance with Provincial Environmental Assessment Certificate Condition No. 7 and Federal Decision Statement Condition Nos. 8.4.3 and 8.4.4 for the Site C Clean Energy Project (the Project). The Site C Reservoir Tributaries Fish Community and Spawning Monitoring Program (Mon-1b) represents one component of the FAHMFP and aims to determine the effects and effectiveness of mitigation measures of the Site C Clean Energy Project (the Project) on fish populations and their habitat that migrate to tributaries of the reservoir. A subcomponent of this monitoring program (Task 2b) aims to assess spawning populations of Bull Trout (*Salvelinus confluentus*) in the Halfway Watershed. Data collected for this task will be used to directly address the following management question and hypotheses:

How does the Project affect Peace River fish species that use Site C Reservoir tributaries to fulfil portions of their life history over the short (10 years after Project operations begin) and long (30 years after Project operations begin) terms?

H_0: There will be no change in Bull Trout spawner abundance in the Halfway River relative to baseline estimates.

H_1: Bull Trout spawner abundance in the Halfway River will decline by 20 to 30% relative to baseline estimates.

Historic data on the Halfway River meta-population have been collected through various spawner assessment methods, including aerial, ground, and snorkel surveys of Bull Trout redds (Diversified Environmental Services and Mainstream Aquatics Ltd. 2009; 2011; 2013). These peak redd counts provide a baseline index of spawner abundance and continued population monitoring pre- and post-construction of the Project is required to test the management question and hypotheses. Previous baseline data will provide an important contribution to evaluating population status prior to the construction of the Project. Revised methods used in this program aim to provide more accurate estimates of Bull Trout redd abundance and reflect associated uncertainties in these estimates, while still maintaining the utility of historic data.

2 Introduction

Salmonid breeding population sizes have been estimated through a variety of methods (Hilborn et al. 1999, Rand et al. 2007, Braun et al. 2017), including redd count surveys. Bull Trout (*Salvelinus confluentus*) population sizes have previously been assessed using redd count surveys in key spawning tributaries of the Halfway Watershed (Diversified Environmental Services and Mainstream Aquatics Ltd. 2009; 2011; 2013). Unlike visual surveys that count the number of spawning adults, redd count surveys provide an index of effective population size (i.e., number of reproducing adults) (Gallagher et al. 2007). Redd counts can also provide the advantage of lower operating costs as the surveys do not rely on large-scale fish tagging efforts associated with mark-recapture surveys (Gallagher et al. 2007).

The main limitation of visual count surveys is their subjective nature, which relies on the ability of each surveyor to minimize the error associated with their observations. The primary sources of error are: (1) observer efficiency (OE; bias towards over- or underestimating redd abundance on any survey), (2) not accounting for redd survey life (SL; the length of time a redd can be detected or counted by an observer), (3) poor temporal coverage of surveys (too few surveys or surveys not covering the peak spawning period), (4) poor spatial coverage (only surveying likely spawning areas or areas convenient to access). If these sources of uncertainty are not accounted for and temporal and spatial coverage is poor, inference can be greatly reduced, as is the confidence one can have in resultant population estimates.

Observer efficiency can vary among individual observers, survey days and systems (Grant et al. 2007, Muhlfeld et al. 2006). Observer efficiency is the ratio of the number of redds observed *versus* the true number of redds present. Observer efficiency values less than one indicate a bias to underestimating redd abundance by the surveyor (e.g., missed redds because of multiple overlapping redds and/or redds hidden by large woody debris or overhanging vegetation). Observer efficiency values greater than one suggest overestimation of redds (e.g., counting a 'test' redd rather than an actual redd, mistakenly assigning a scour feature as a redd, or double-counting). Both sources of error are common to any form of visual stock assessment survey methodology but the degree to which each contributes to error in population estimates depends on the unique set of survey conditions such as water clarity, depth, light conditions, habitat complexity, and redd density as well as observer experience (Gallagher and Gallagher 2005).

Quantifying the within- and among-site variability in Bull Trout redd survey life can further reduce the error associated with double counting redds over consecutive surveys. Digging of redds by spawning females scours the substrate, removing periphyton and fine sediments and exposing clean substrate. The visible contrast between scoured and periphyton-covered rocks enables the identification of redds. After eggs have been fertilized and buried, periphyton and fine sediments will recolonize and settle on the clean substrate. The amount of time before redds become indistinguishable from the rest of the stream bed can vary between systems and species. Accurate estimates of redd survey life are essential to reduce the inaccuracies associated with the amount of time a redd is 'surveyable'.

Adequate temporal coverage of surveys is important for generating reliable estimates of spawn-timing and redd abundance (Holt and Cox 2008). Estimates based on peak counts fail to account for variability in migration timing and spawning behaviour, and abundance estimates derived from a limited number of surveys are associated with high uncertainty and are often inaccurate (Holt and Cox 2008). Inadequate spatial coverage can also bias estimates low by focusing only on obvious spawning locations or locations that are most accessible.

Area-under-the-curve (AUC) methods can incorporate OE and SL when estimating population abundance. This approach is widely used to estimate the number of spawners or redds in a river from visual count data (Hilborn et al. 1999). Estimating OE and SL can be challenging and cost prohibitive, however these parameters are fundamental to the AUC calculation. There are many versions of AUC models that employ a range of run- or spawn-timing models and estimation procedures (Holt and Cox 2008) and whether they incorporate uncertainty. For example, Millar et al. (2012) developed a Gaussian AUC (GAUC) approach that uses a normally distributed timing model with maximum likelihood estimation, and allows for uncertainty in OE and SL to be incorporated. This approach outperformed other commonly used AUC approaches such as the Trapezoidal method and was robust to assumptions of a normal timing model when estimating the number of Pink Salmon (Millar et al. 2012).

Since 2002, Bull Trout redds have been enumerated during some years in six tributaries of the Halfway Watershed (Figure 1) (Diversified Environmental Services and Mainstream Aquatics Ltd. 2013). During the survey years of 2008, 2010 and 2012, four of the original six tributaries were consistently enumerated (Chowade River, Cypress Creek, the Upper Halfway River, and Needham Creek; Table 1), and two additional tributaries were surveyed in 2010 (Fiddes and Turnoff Creeks). Redd counts during these surveys were conducted using a variety of visual survey methods, including ground, snorkel, and aerial surveys. Survey efforts have primarily focused on established Wildlife Habitat Areas (British Columbia Ministry of Environment), but additional reaches, of varying lengths, have been surveyed in some years. While these surveys provide valuable baseline information on the extent of Bull Trout spawning in each tributary and population sizes prior to the construction of the Project, estimates are based on only two surveys per season and did not consider key parameters such as OE and SL, which could reduce their accuracy.

Redd counts provide an index of the number of females that successfully deposited eggs. However, in populations where female size varies, redd counts may not accurately represent the number of eggs deposited. For example, larger females produce more eggs (Kindsvater et al. 2016) and build larger redds (Riebe 2014). Accounting for redd size could increase the reliability of redd estimates as an indicator of juvenile recruitment and provide a more direct link to juvenile data being collected under Mon-1b, Task 2c (Golder Associates Ltd. 2016). Furthermore, redd size may provide information on the relative number of resident *versus* migratory Bull Trout in tributaries of the Halfway Watershed. This could be achieved by directly linking female length and fecundity to redd size through coordination among Site C FAHMFP monitoring programs that capture, tag and track adult Bull Trout to their spawning grounds.

The objective of the current monitoring program is to standardize data collection methodology and estimate redd abundance to provide accurate information on Bull Trout population status over time while minimizing and quantifying uncertainty. Accurate estimates of Bull Trout redd abundance will be achieved through estimation of uncertainty in OE and SL using GAUC models. In addition, increasing the number of redd surveys over longer time periods will provide more reliable information on spawn timing and redd abundances. Finally, accounting for redd size will provide a more direct link to the number of eggs deposited in each tributary. This approach provides an increased ability to track changes in Bull Trout population size over time to inform effective mitigation measures for migratory Bull Trout moving upstream and downstream of the Project.

3 Methods

3.1 Study Sites

We surveyed five key spawning tributaries of the Halfway Watershed (Figure 1[1]). Selection of these streams and survey areas was based on previous studies that examined spawning and migration patterns from radio telemetry data (Diversified Environmental Services and Mainstream Aquatics Ltd. 2009; 2011; 2013, and references therein). The Halfway River joins the Peace River 36 km west of Fort St. John. Spawning tributaries range in size from 21 river km (Fiddes Creek) to 304 river km (Halfway River) (Table 1). [REDACTED]. Sites were accessed via helicopter from the Fort St. John airport.

Table 1. Summary of stream characteristics including stream order (equal to 1 plus the *n*th order of two joining stream segments (Platts 1979)), stream magnitude (equal to the sum all stream segments with magnitude of one (Bridge 2003)), and stream length (total length of the stream mainstem). Data are from BC Ministry of Environments Watershed Dictionary Query (http://a100.gov.bc.ca/pub/fidq/viewWatershed Dictionary.do) and are taken from a 1:50 000 scale.

Watershed Code	Name	Order	Magnitude	Length (km)
235	Halfway River	7	3130	303.6
235-430800	Chowade River	5	424	87.1
235-492500	Cypress Creek	5	331	81.7
235-821300	Turnoff Creek	4	47	20.2
235-821600	Fiddes Creek	4	37	21.0

[Figure 1 – REDACTED]

3.2 Visual Surveys

Peak Bull Trout spawning in the Halfway Watershed generally takes place between mid and late September (Diversified Environmental Services and Mainstream Aquatics Ltd. 2009; 2011; 2013 and Braun et al., 2017). We conducted weekly redd count surveys on Cypress Creek, the Chowade River, and the Upper Halfway River system (Upper Halfway River, Fiddes and Turnoff Creeks) for four weeks [REDACTED] (Table 2). Due to helicopter availability and weather conditions in the last week of September, the final surveys were conducted in the first week of October.

[Table 2 – REDACTED]

Each week, two biologists with previous experience assessing or counting salmonid redds and spawners conducted helicopter-assisted redd count surveys over a three-day period (one day per tributary). Surveys consisted of aerial surveys in all known spawning reaches

---

[1] All map images were created in R (R Core Team 2017) using packages *rgdal* (Bivand et al. 2017), *GISTools* (Brundson and Chen 2014), and *sp* (Bivand et al. 2013).

and ground surveys in high-density spawning reaches. Aerial and ground survey reaches were laid out during reconnaissance surveys by InStream Fisheries Research Inc. in 2016 (Braun et al., 2017) and radio telemetry studies performed in the mid-2000s (Diversified Environmental Services and Mainstream Aquatics Ltd. 2013 and references therein). Aerial surveys were typically conducted first, followed by ground surveys. For the Chowade River, Cypress Creek and the Upper Halfway River, aerial surveys were conducted flying in an upstream direction, however direction of travel varied for Fiddes and Turnoff Creeks depending on light and wind conditions. When wind conditions were amenable, the direction flown aimed to minimize glare and maximize visibility. Turbidity can reduce visibility at higher discharges, but water clarity was visually assessed to be >2 m in all tributaries during all surveys and we do not expect turbidity to affect estimates of OE.

Redds were identified as areas with disturbed and cleaned substrate, with an obvious crest at the upstream end of the disturbed area, a tailspill area where disturbed substrate gathered, and a distinct depression between the crest and tailspill (Gallagher et al. 2007). These criteria were confirmed by periodic observations of active spawning during both aerial and ground surveys. Bull Trout redds were often found in overlapping clusters, and the number of redds per cluster was defined as the number of crest-tailspill pairs. While all redd criteria were visible during ground surveys, patches of disturbed and cleaned substrate were the primary characteristics used to identify redds during aerial surveys.

Ground Surveys

Ground survey areas were established in 2016 using historic redd distributions and pre-defined Wildlife Habitat Areas (Braun et al., 2017, Diversified Environmental Services and Mainstream Aquatics Ltd. 2009; 2011; 2013). No ground survey was conducted on Turnoff Creek because the helicopter could not be safely landed. Ground surveys were performed in reaches established in 2016, apart from the Chowade River, for which the ground reach was shortened by ~1 km. Redd densities were high in the Chowade River ground reach and the reach was shortened to reduce survey time while still maintaining adequate redd counts to estimate OE. The lengths of ground reaches ranged from 1.5 to 4 km (Table 3). The Cypress Creek ground reach was not assessed on Survey 1 due to helicopter safety issues, and therefore only three ground surveys were performed on Cypress Creek.

Surveys began at the upstream boundary of ground survey areas and progressed downstream to meet the helicopter at the lower boundary. When side channels were present, one observer followed the side channel while the other continued on the mainstem. When more than two channels were present, observers would double back to count all remaining channels. All redds were counted and geo-referenced using a handheld GPS (Garmin Monterra, Garmin, Schaffhausen, Switzerland) accurate to ± 3 m. A subset of redds were also systematically marked to collect data for estimating OE and SL (see Section 3.3, Redd Marking). All spawning Bull Trout observed were also enumerated (Appendix 1).

Aerial Surveys

Aerial surveys were conducted via helicopter flying 50 to 100 m above ground at flight speeds of 15 to 40 km hr^{-1}. Aerial survey methods described herein are based on established DFO protocols (Trouton 2004). Teams surveyed the river channel from the side doors of the helicopter while the pilot flew at an angle to ensure adequate visibility. One observer was in the front passenger seat (port side) and transcribed data, while the second observer was in the back-passenger seat (port side) and called out the number of redds and spawning Bull Trout as they were observed. Observers used high-quality polarized glasses to reduce glare off the water surface. Aerial surveys were typically conducted at mid-day when the sun was directly over head and visibility conditions were optimal, but this varied based on weather conditions. Total redd counts within the aerial survey reach were recorded noting redd location with the GPS. If clusters of redds were observed, we recorded the estimated number of redds.

Aerial surveys covered the entire length of ground survey reaches, allowing aerial OE to be estimated through comparison of aerial and ground counts. The method of comparing aerial and expanded ground counts is robust to the assumption of ground surveys being more accurate than aerial surveys. Ground surveys are considered more accurate than aerial surveys because the surveyor has more time to examine the river for redds and can more accurately assess false redds (e.g., ‘test’ redds, scour features, beaver activity) and clusters of redds. Although OE for redd counts from ground surveys are often close to 1 (Gallagher et al. 2007), there may be situations when aerial surveys are more efficient than ground surveys. For example, aerial surveys may be more accurate in a wide, fast flowing section of river that is challenging to see from ground level. Aerial OE will be <1 when the assumption of more accurate ground counts is met (i.e., the number of expanded redds from the ground surveys would be greater than the aerial surveys), and >1 when the assumption is not met (i.e., the number of redds counted during the aerial surveys would be greater than the expanded number of redds from the ground surveys).

Table 3. Summary of redd survey reaches. Distances are in river km.

Tributary	Ground Survey Length (km)	Direction Walked	Aerial Survey (km)	Direction Flown
Chowade River	4	Downstream	27	Upstream
Cypress Creek	2.5	Downstream	18.5	Upstream
Fiddes Creek	2.0	Downstream	14.8	Variable
Turnoff Creek	-	-	15.0	Variable
Upper Halfway River	1.5	Downstream	22.5	Upstream

3.3 Redd Marking

During ground surveys, redds were marked by inserting a bristle tag with a 12-inch stake into the crest of the redd. Green bristle tags were selected to enable surveyors to re-observe redds during consecutive surveys but not draw the observer’s eyes to the tag before the redd itself was observed. Colour choice resulted from trials of red, green, white, and yellow tags performed in 2016 (Braun et al., 2017). A small label containing a unique redd number was attached to each tag and redds were tracked throughout the spawning period. When a redd was no longer identifiable, the tag was removed and the redd was not enumerated. We marked almost all accessible redds during ground surveys to maximize the accuracy of ground OE. We did not mark redds that were too deep to safely access, and when large clusters of redds were encountered, we marked only the most prominent upstream redd.

Redd characteristics were recorded following the methods of Gallagher et al. (2007). The unique redd identifier (redd tag number) was recorded along with the date, GPS location, age class, and whether the redd was observable (see Section 3.4, Survey Life). In addition, redd dimensions (length and width) were measured to the nearest centimeter. Length was defined as the distance between the upper crest of disturbed substrate to the end of the tailspill, and width was the distance of disturbed substrate measured perpendicular to the length axis.

3.4 Redd Abundance

Observer Efficiency

During ground surveys, surveyors enumerated the number of marked and unmarked redds. Observer efficiency was estimated by dividing the number of marked redds observed by the number of marked redds available to be observed. This is similar to the estimation of OE for visual surveys using mark-recapture methods (Melville et al. 2015). The number of redds observed in the ground survey reach was expanded to a total number of redds by dividing the number of observed redds by the mean ground survey OE. A key assumption was that there was no tag loss; this was assessed by deploying 10 test tags in each tributary and counting the number of tags in each survey to determine the proportion lost over the survey period. In 2017, all tags were recovered from each of the four tributaries during the final survey in the first week of October.

Observer efficiency for aerial surveys was estimated by conducting aerial counts over the ground survey reaches. The total ground and aerial redd counts were compared within the ground survey reach. For example, if ground surveys counted 12 redds and the ground OE was 0.75, the estimated total number of redds in the ground reach would equal 16. If 8 redds were observed during the aerial survey over the ground reach, the aerial OE would be calculated as 8/16 = 0.5. For GAUC models, we used the mean and standard error of aerial survey OE specific to each tributary to expand aerial counts. This method for calculating OE for aerial surveys is relatively novel, and combines conventional methods for estimating OE.

Ground surveys were not conducted on Turnoff Creek and during GAUC estimation we used surrogate aerial OE values from Fiddes Creek, a nearby tributary with similar substrate and flow characteristics. Because we only completed three ground surveys on Cypress Creek, only two ground OE values could be calculated and averaged to determine aerial OE. During the first survey of Fiddes Creek, the field GPS lost satellite reception and the location of aerial redds could not be recorded. Although we obtained an aerial count for Survey 1, we could not determine the proportion of redds that were within the boundaries of the ground reach, and therefore we could not calculate an aerial OE for Survey 1 in Fiddes Creek.

Survey Life

Survey life was estimated by assigning redd age class and was tracked for marked redds over consecutive surveys. Redd age class was recorded following the methods of Gallagher et al. (2007):

Age-1 = new since last survey but clear;

Age-2 = still measurable but already measured;

Age-3 = no longer measurable but still apparent;

Age-4 = no redd apparent, only a tag (at which point the tag will be removed); and

Age-5 = poor conditions; cannot determine if present and measurable or not.

Survey life is the number of days a redd is observable and available to be counted. In the current study, this was determined during ground surveys and applied to aerial surveys during GAUC estimation. We did not attempt to estimate the SL of redds for aerial surveys.

We estimated mean survey life using a linear mixed effects model of survey date *versus* redd age class (using 2017 redd age data). Survey life likely varies between tributaries, and we tested the effect of adding tributary as a fixed effect to the mixed effect model (to increase the sample size we combined redd age data from 2016 and 2017). The linear model related normalized survey day (day 1 was the day each redd was first observed and tagged) to the assigned redd age class. Linear mixed effects modelling was performed in R (R Core Team 2017) using *lme4* (Bates et al. 2015). We defined SL as the predicted normalized survey day at which redds became age-4, or no longer apparent. As random effects we added intercepts for each tag id and allowed by-tag id random slopes for the effect of redd age class. The redd age class model for predicting the normalized survey day was:

$$y_{i,t} = (a + \theta_i) + (b + \mu_i) r_{i,t} + \varepsilon_{i,t} \tag{1}$$

$$\theta \sim N(0, \sigma^2),$$

$$\mu \sim N(0, \sigma^2),$$

$$\varepsilon \sim N(0, \sigma^2)$$

where the y is the normalized survey day for redd i, on survey t (t = 3, 4, or 5), a is the mean intercept and θ is the random variation around the mean intercept, b is the slope for the effect of redd age class (r) on the normalized survey day, μ is the random variation around the mean slope b, and ε is the residual error. Estimates of θ, μ and ε are assumed to be normally distributed with a mean of zero.

Survey life is dependent on physical and biological conditions such as flow, substrate type, and periphyton growth, and likely varies among tributaries in the Halfway Watershed. We combined redd age data from 2016 and 2017 and examined the effect of tributary on predicted SL by adding a fixed effect of tributary to the model in Equation 1.

Trail Cameras

Building off work completed in 2016, we conducted a pilot program in 2017 to explore the use of trail cameras to verify SL assumptions and examine Bull Trout spawning behaviour. Redd age was assessed once per week during ground surveys, while the trail cameras provided daily redd age data that could be used to determine the exact day a redd moved to a higher age class. We deployed one trail camera (Defender 850, Browning, Morgan, Utah, USA) on a redd in both the Chowade and Upper Halfway Rivers (Figure 1). Trail cameras were installed during the second ground survey in the second week of September and removed during the last survey in the first week of October. We installed the cameras on age-1 redds with active Bull Trout spawning behaviour. Both redds had been tagged as age-1 during the first ground survey. The cameras were mounted to trees proximate to the redd and time lapse photos were taken each hour for the entire survey period (21 days). Additional photos were taken when the camera's motion-sensing feature was triggered (e.g., wildlife disturbance).

GAUC Estimates

We used a GAUC method to estimate the total number of redds for each system. Visual fish stock assessment data can be modelled as a quasi-Poisson distribution with spawn-timing described by a normal distribution and parameter estimates evaluated using maximum likelihood estimation (described in Millar et al. 2012). Spawn-timing is defined as the timing of new redd establishment throughout the spawning season. An advantage of this GAUC approach over conventional forms of AUC and peak count indices from baseline surveys is the ability to incorporate variance in OE and SL, fit spawn-timing using maximum likelihood estimation, and estimate the associated uncertainty in redd abundance.

With abundance modelled as a quasi-Poisson distribution with normally distributed spawn-timing (Millar et al. 2012), the number of observed redds at time t (C_t) is

(2)
$$C_t = a\ exp\left[-\frac{(t-m_s)^2}{2\tau_s^2}\right]$$

where a is the maximum height of the redd count curve, m_s is the time of the peak number of redds, and τ_s^2 is the standard deviation of the arrival timing curve.

Because the normal density function integrates to unity, the exponent term in Equation 2 becomes $\sqrt{2\pi\tau_s}$ and Equation 2 can be simplified to

(3)
$$C_t = a\sqrt{2\pi\tau_s}$$

A final estimate of abundance ($\hat{E}$) is obtained by applying OE (v) and SL (l) to the estimated number of observed redds

(4)
$$\hat{E} = \frac{\hat{F}_G}{l * v}$$

$\hat{E}$ in Equation 4 is estimated using maximum likelihood (ML), where $\hat{a}$ and $\hat{\tau}$ are the ML estimates of a and τ_s in Equation 3 ($\hat{C}_t = \hat{a}\sqrt{2\pi\hat{\tau}_s}$).

The GAUC estimation in Equation 2 can be re-expressed as a linear model, allowing the estimation to be performed as a simple log-linear equation with an over-dispersion correction factor. The over-dispersion correction accounts for instances where the variance of the redd observations exceeds the expected value. The log-linear model is computationally simple and can be completed using standard generalized linear modelling. The estimated number of fish-days ($\hat{F}_G$) can be estimated following

(5)

$$\hat{F}_G = \sqrt{\frac{\pi}{-\hat{\beta}_2}} exp\left(\beta_0 - \frac{\hat{\beta}_1^2}{4\hat{\beta}_2}\right)$$

where β_0, β_1, β_2 are the regression coefficients of the log-linear model. Uncertainty in OE and SL are incorporated into the estimated redd abundance using the covariance matrix of the modeled parameters (β_0, β_1, β_2) via the delta method (described in Millar et al. 2012).

Mean estimates for abundance and input parameters are presented along with standard error, 2.5% and 97.5% confidence limits, and percent relative uncertainty (%RU), which is defined as:

(6)

$$\%RU = \left(\frac{|v - \mathrm{SE}|}{v}\right) \cdot 100$$

where v is the mean estimate, SE is the standard error of the mean, and the vertical lines indicate the absolute value.

Zero counts at the beginning and end of the spawning period were estimated for all tributaries (Bue et al. 1998). At the beginning of spawning, zero counts were assigned a week before the first survey. The zero count at the end of spawning was assigned a date that was equal to the number of days estimated for the redd survey life after the last new redd was observed (i.e., Survey 4). This ensured that the last redds observed would not be observable (redd age-4) on the zero-count date. The influence of adding zero counts is examined in Appendix 2.

To continue the peak count indices previously reported (Diversified Environmental Services and Mainstream Aquatics Ltd. 2013), we calculated the peak count index following the methods described in Diversified Environmental Services and Mainstream Aquatics Ltd. (2013). In the past, redd counts were conducted during one or two survey weeks. [REDACTED]. Each reach of the river was surveyed by one of three survey types: (1) aerial, (2) ground, and (3) snorkel. The exact dates depended on weather and the number of tributaries surveyed each year. The peak count index was calculated for each tributary by adding redds that were observed on the first survey but not on the second survey to the total number of redds counted during the second survey. [REDACTED].

3.5 Redd Area, Fish Length and Fecundity

We measured the length and width of all redds marked during ground surveys to the nearest centimeter. Redd area was calculated assuming an elliptical shape:

(7) $$A = \pi LW$$

where A is the area of the disturbed stream bed, L is the length of the redd measured from the crest to the tailspill and W is the maximum width of the disturbed stream bed perpendicular to the length axis.

We predicted fork-length from measured redd area using the redd area-fork length relationship defined in Riebe et al. (2014). The authors used individuals from three species of Pacific Salmon (Sockeye, Pink and Chinook Salmon). In their study, redd area was measured at a greater resolution than in the current study and therefore better represents actual redd area. The relationship between redd area and fork length was estimated to be:

(8) $$A = 3.3\left(\frac{L}{600}\right)^{2.3}$$

where A is redd area in m^2, L is the female fork length in mm and 600 is a reference value that was near the average length of individuals in their study. The model was based on 60 observations and was highly significant with a correlation coefficient (r) of 0.89 and a p-value <0.001.

The redd area equation was transformed to solve for fork length:

(9) $$L = \left(\frac{600^{2.3}\mathrm{A}}{3.3}\right)^{0.434783}$$

Published data on Bull Trout lengths and egg number were used to determine the length-fecundity relationship. Data were extracted from a review of Bull Trout life histories by McPhail and Baxter (1996), which included length and egg number data for six populations (Figure 3). The equation for the regression line used to estimate egg number is:

(10) $$\ln(E) = -8.434 + 2.606\ln(\mathrm{L})$$

where E is the number of eggs per female and L is the female's fork length in mm.

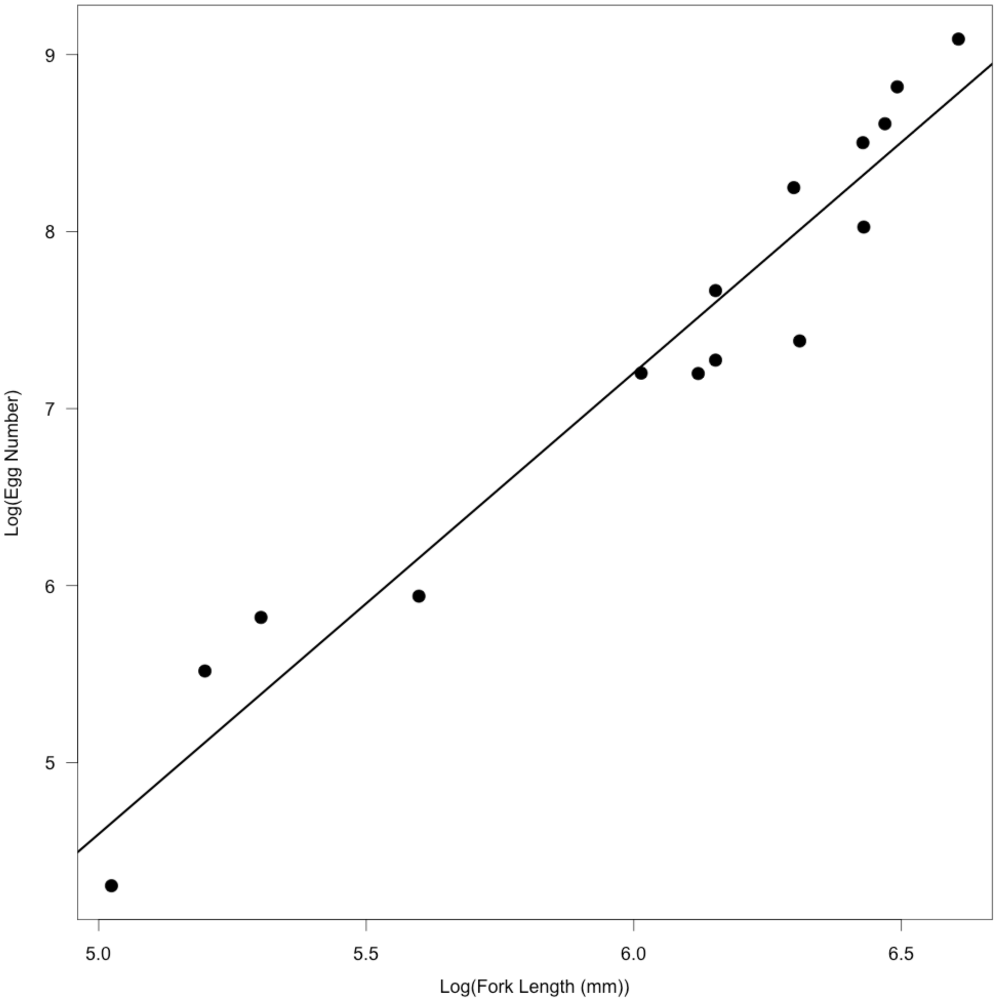

Figure 2. Published data of Bull Trout female fork length by egg number. Both axes are on the natural log scale. The model R^2 was 0.94 and the p-value was <0.0001.

4 Results

4.1 Redd Distribution

In the Chowade River, redds were distributed throughout the survey area in all four surveys. There were several areas with higher redd densities, including higher densities within the ground survey reach (Figure 4). [REDACTED].

Redds were relatively evenly distributed in Fiddes and Turnoff Creeks (Figure 6), rather than in high- and low-density areas as observed in Cypress Creek and the Chowade River. [REDACTED].

In the Upper Halfway River, the highest densities of redds were observed near the upstream boundary of the aerial reach, within the ground survey area (Figure 6). [REDACTED].

[Figure 3 – REDACTED]

[Figure 4 – REDACTED]
[Figure 5 – REDACTED]

4.2 Redd Abundance

Observer Efficiency

Observer efficiencies for ground surveys were calculated from the re-sighting of marked redds in all tributaries except in Turnoff Creek, where ground surveys were not conducted. Observer efficiency for ground surveys was estimated for Surveys 2, 3, and 4, and were relatively high and consistent among surveys and within tributaries (Table 4). Ground OE was >85% for all four tributaries, while aerial OE ranged from 0.11 to 0.55. Mean aerial OE was relatively consistent among the four tributaries but varied among surveys. In the Chowade River and Cypress Creek, mean aerial OEs were 0.26 (CV 61%) and 0.28 (CV 44%), respectively, while aerial OE was 0.39 (CV 43%) in Fiddes Creek and 0.37 (CV 38%) in the Upper Halfway River.

Table 4. Summary of ground and aerial counts and calculated observer efficiencies. Ground count OEs for Surveys 2 through 4 are in parentheses. Aerial counts are for only the portion of river that ground surveys were conducted in. NA denotes either the lack of data or values that could not be calculated.

Tributary	Number of Redds Marked	Mean Ground OE	Survey	Ground Count	Total Redds[a]	Aerial Count[b]	Aerial OE[c]
Chowade River	39	0.93 (1.0, 1.0, 0.86)	1	19	20.4	3	0.15
			2	52	55.9	25	0.45
			3	78	83.9	28	0.33
			4	44	47.3	5	0.11
Fiddes Creek	7	0.88 (1.0, 0.86, 0.80)	1	5	5.7	NA	NA
			2	9	10.2	4	0.39
			3	8	9.1	5	0.55
			4	4	4.5	1	0.22
Upper Halfway River	20	0.95 (1.0, 0.88, 1.0)	1	5	5.3	1	0.19
			2	26	27.4	11	0.40
			3	34	35.8	19	0.53
			4	35	36.8	13	0.35
Cypress Creek	14	0.95 (NA, 1.0, 0.92)	1	NA	0.0	NA	NA
			2	7	7.4	3	0.41
			3	15	15.8	4	0.25
			4	11	11.6	2	0.17

---

a: Ground count / ground observer efficiency
b: Aerial count within ground reach
c: Aerial count / total redds

Survey Life

A total of 73 tags were applied to redds during 2017 ground surveys in Fiddes Creek, Cypress Creek, the Chowade River, and the Upper Halfway River. Of these 73 tags, 38% (28 redds) progressed to age-4 during the survey period. The number of tags that progressed to age-4 was 43% in the Chowade River, 70% in Cypress Creek, 43% in Fiddes Creek, and 11% in the Upper Halfway River. A summary of redd ages observed in each survey is presented in Table 4.

We estimated mean SL for 2017 using a linear mixed effect model of normalized survey day and age class. The model allowed the SL to be estimated using age data collected from all marked redds, despite not all redds progressing to age-4. The mean SL estimated by the model was 24.2 days (Figure 6), with a standard of 2.3 days after accounting for the uncertainty in the fixed effect of redd age, the variance in random slopes for redd age, and the variance in intercepts for marked redds. A visual inspection of model residuals suggested the redd age data adequately met the assumptions of linearity and homoscedasticity.

Table 5. Redd ages observed in ground reaches in Surveys 1 through 4 in the Halfway Watershed. NA denotes the lack of data due to helicopter safety issues.

Tributary	Survey	Redd Count by Age Class			
		Age-1	Age-2	Age-3	Age-4
Chowade River	1	8	0	0	0
	2	17	6	2	0
	3	12	21	2	2
	4	0	2	15	14
Cypress Creek	1	NA	NA	NA	NA
	2	3	0	0	0
	3	7	1	2	0
	4	0	1	1	7
Fiddes Creek	1	5	0	0	0
	2	2	3	2	0
	3	0	2	2	2
	4	0	0	3	1
Upper Halfway River	1	5	0	0	0
	2	11	4	1	0
	3	3	10	3	1
	4	0	10	7	1

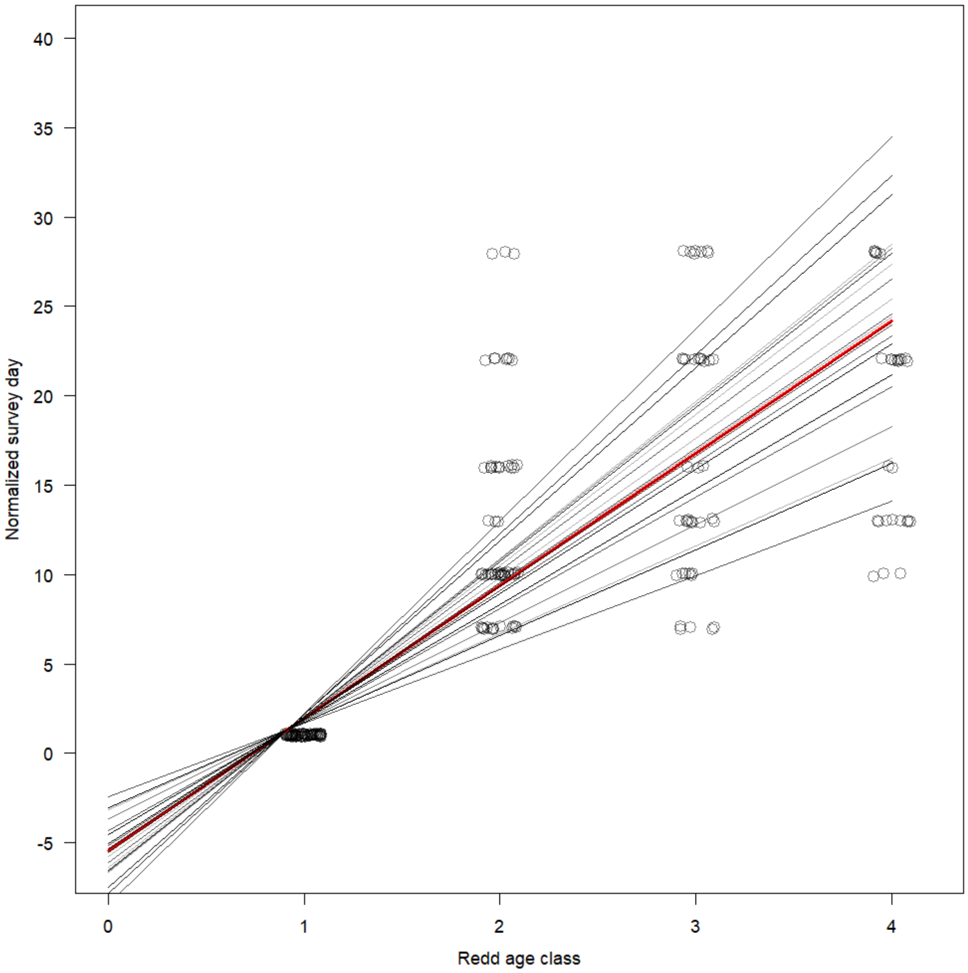

Figure 6. Redd age by normalized survey day. Points are jittered for presentation, and grey lines are random slopes and intercepts. Red line represents the mean fixed effect. Negative normalized survey days correspond to the number of days between the redd being built and the first observation by surveyors. A normalized survey day of 1 is when the redd was first observed by surveyors. See Equation 1 for model details.

We examined the effect of tributary on predicted SL by adding a fixed effect of tributary to the linear model. First, we combined redd age data from 2016 and 2017 and predicted SL using the linear model in Equation 1. The predicted SL for redd age data from 2016 and 2017 combined was 20.9 days with a standard error of 2.9 days. Residual analysis suggested the assumptions of linear modelling were met. We then added a fixed effect of tributary to the model in Equation 1 and predicted SL for each tributary. Predicted SL was 20.1 days for the Chowade River, 16.1 days for Cypress Creek, 22.4 days for Fiddes Creek, and 24.1 days for the Upper Halfway River. We examined the significance of the fixed tributary effect using a likelihood ratio test of the full model to the model without the effect of tributary. The p-value of the likelihood ratio test was 0.197, suggesting the effect of tributary was not significant in the SL model. During GAUC estimation, we used the SL estimated by the linear mixed effects model of normalized survey day *versus* redd age (24.2 days) without the fixed effect of tributary (2017 data only).

Trail Cameras

The Chowade River trail camera provided daily redd age data for a redd tagged at age-1 in Survey 1 [REDACTED]. The camera was installed in Survey 2 [REDACTED] when the redd was still assessed as age-1 (spawning Bull Trout were present) and was removed in Survey 4 [REDACTED] at a redd age of 3. Three Bull Trout were observed using the redd in the one-week period following camera installation. One fish appeared to be a male while the other two appeared to be females based on size and physical characteristics. The last Bull Trout was observed using the redd on [REDACTED], and the redd therefore turned age-2 on [REDACTED] (see Appendix 3 for example photos). During ground surveys, however, crews assessed the redd as age-2 on [REDACTED] and age-3 on [REDACTED]. Due to glare and poor lighting, the pictures from the Upper Halfway River trail camera could not be used in 2017.

GAUC Estimates

The maximum likelihood estimates for Bull Trout redd abundance varied 18-fold among the surveyed tributaries (Table 6). Redd abundance ranged from 18 to 320 for Turnoff Creek and the Chowade River, respectively. The %RU in the abundance estimates ranged from 53.3% (Cypress Creek) to 76.0% (Upper Halfway River). The arrival timing model fit the count data well for all tributaries except Turnoff Creek, where relatively flat aerial counts made estimating the start of redd deposition difficult (Figure 8).

Peak count indices were calculated following Diversified Environmental Services and Mainstream Aquatics Ltd. (2013) methods for comparison between baseline estimates and GAUC estimates. We found a 40-fold difference between the lowest (3 in Turnoff Creek) and highest (116 in the Chowade River) peak count estimates of redd abundance among tributaries, and the peak count method consistently underestimated redd abundance relative to the GAUC method (Table 7). More specifically, the GAUC estimates were between 2.4 (Cypress Creek and Upper Halfway River) and 6-fold (Turnoff Creek) higher than peak count indices. The peak count indices for Cypress and Turnoff Creeks and the Chowade River fell within the confidence limits of the GAUC estimate, while peak counts for Fiddes Creek and the Upper Halfway River were outside of the GAUC lower confidence boundary.

Table 6. GAUC estimates for Bull Trout redd abundance. OE and SL means and standard errors are input parameters for the AUC models. The 95% confidence limits are the 2.5 and 97.5% confidence bounds. Standard errors are in parentheses. OE is estimated by comparing the aerial counts observed within the ground reach to the number of redds estimated to be in the ground reach. Survey life is estimated by aging marked redds and predicting mean survey life from the redd age model described in Equation 1.

Tributary	GAUC Abundance	2.5% CL	97.5% CL	%RU	Aerial OE	Survey Life	Peak Count Index
Chowade River	320 (109)	164	625	65.9	0.26 (0.079)	24.2 (2.3)	116
Cypress Creek	90 (42)	36	223	53.3	0.28 (0.071)	24.2 (2.3)	38
Fiddes Creek	63 (18)	36	110	71.4	0.39 (0.095)	24.2 (2.3)	18
Turnoff Creek	18 (8)	8	41	55.6	0.39 (0.095)	24.2 (2.3)	3
Upper Halfway River	75 (18)	47	119	76.0	0.37 (0.070)	24.2 (2.3)	31

Table 7. Current and baseline estimates of Bull Trout redd abundance. From 2002 to 2012, peak count estimates are provided, and for 2016 and 2017, GAUC and peak count estimates are presented. Surveys for peak counts varied in the length of stream surveyed and survey method among years within tributaries. NS denotes a year in which no surveys were conducted.

	Peak Counts								GAUC	
Tributary	2002	2004	2007	2008	2010	2012	2016	2017	2016	2017
Chowade River	104	210	NS	425	864	321	108	116	290	320
Cypress Creek	NS	NS	17	120	60	62	33	38	90	90
Fiddes Creek	NS	NS	NS	NS	146	59	20	18	107	63
Turnoff Creek	NS	NS	NS	NS	56	40	9	3	44	18
Upper Halfway River	NS	NS	11	23	86	33	16	31	20	75
Needham Creek	NS	NS	29	78	103	80	NS	NA	NS	NS

[Figure 7 – REDACTED]

4.3 Redd Area, Fish Length and Fecundity

The mean redd area varied almost 2-fold among tributaries (Figure 9). The largest redds were observed in the Upper Halfway River (mean redd area: 2.37 m^2), followed by the Chowade River (1.75 m^2) and Fiddes Creek (1.72 m^2), while the smallest redds were observed in Cypress Creek (1.29 m^2). Variation in redd area was similar in the Upper Halfway River (CV = 58%), Chowade River (CV = 55%), and Cypress Creek (CV = 57%) and lower in Fiddes Creek (CV = 23%). Predicted mean fork lengths varied 1.3-fold among tributaries while the predicted number of eggs per female varied over 2-fold (Table 8).

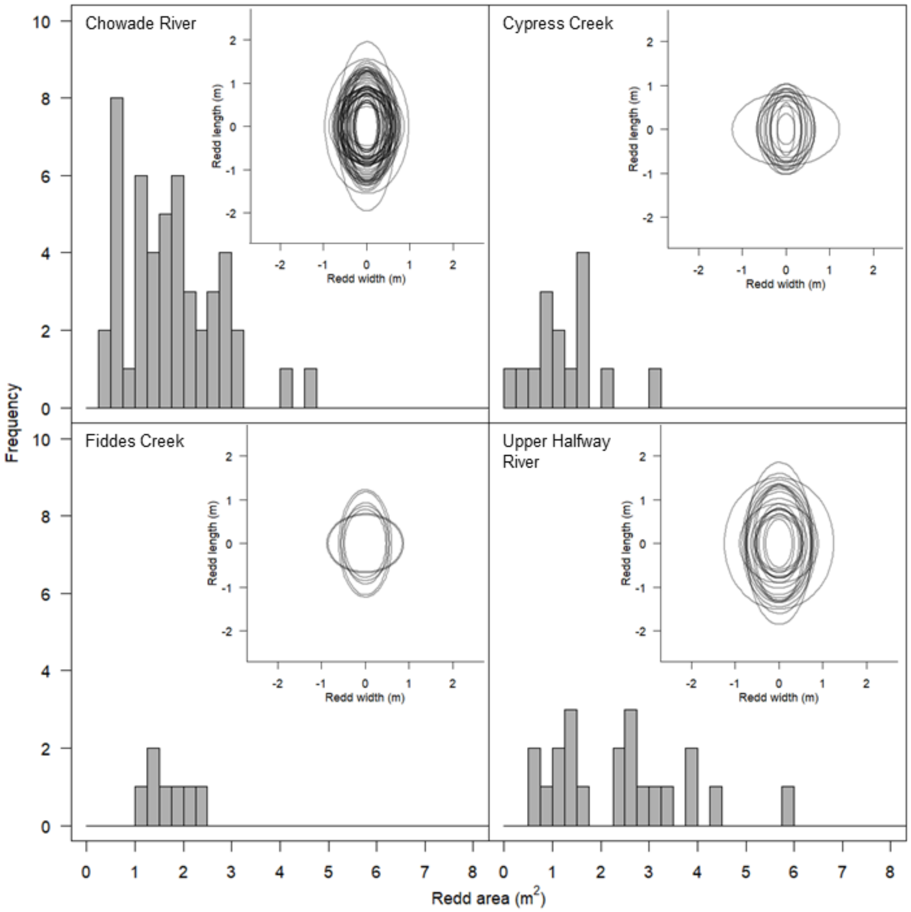

Figure 8. Frequencies of redd area by tributary. Insets represent the shape of redds based on lengths and widths and an assumed elliptical shape. Redds are centered at the origin of the inset plots (0,0).

Table 8. Summary of predicted mean fork lengths and egg number from redd area by tributary using Equations 7, 8 and 9. Ranges are in parentheses.

Tributary	Fork Length (mm)	Egg Number
Chowade River	455 (247-703)	1837 (374-5707)
Cypress Creek	399 (185-590)	1304 (176-3615)
Fiddes Creek	452 (381-514)	1805 (1157-2524)
Upper Halfway River	520 (269-772)	2601 (467-7285)

5 Discussion

As part of a multi-year project, aerial and ground surveys were conducted on five key Bull Trout spawning tributaries of the Halfway Watershed. We used estimates of OE and SL in a GAUC model to estimate the mean redd abundance with associated uncertainty for each tributary. A peak count index of redd abundance was calculated for comparison with baseline data. Finally, we measured redd size to provide additional information on egg deposition and thus juvenile recruitment.

5.1 Redd Distribution

Redd distributions within tributaries and across surveys in 2017 were similar to the distributions observed in historic surveys (Diversified Environmental Services and Mainstream Aquatics Ltd. 2009; 2011; 2013) and in 2016 (Braun et al. 2017). Aerial and ground survey methods were the same in 2016 and 2017, allowing for more detailed comparisons of redd distribution between the two survey years.

In the Chowade River, there was temporal variation in the redd distribution in 2016, whereby the upper portions of the survey area were occupied earlier than lower reaches. We did not observe this colonization pattern in 2017, and redds were more evenly distributed throughout the survey reach at the onset of spawning. In 2016, redds were observed at the upstream boundary of the aerial survey area, however in 2017, we observed only one redd in the uppermost 2 km of the survey reach. Discharge in the Chowade River was lower in 2017 relative to 2016, which may explain why Bull Trout did not migrate and spawn as far upstream as in 2016.

Redd distribution in Cypress Creek and the Upper Halfway River were similar in 2016 and 2017. In both tributaries, there were distinct spawning areas separated by kilometers of river where no spawning was observed. Areas lacking evidence of spawning activity were often low gradient sections with inappropriate spawning substrate. [REDACTED].

In Fiddes and Turnoff Creeks, very few redds were observed in Survey 1 [REDACTED], suggesting the spawning timing may be later in these tributaries relative to the larger tributaries. In 2017, we did not observe redds in the uppermost 5 km of the Fiddes Creek survey area, despite some of the highest redd densities occurring there in 2016. Redds were evenly distributed throughout the lower reach in both survey years. The distribution of redds likely shifted downstream in Turnoff Creek in 2017, however redd counts were low in both years, making it difficult to compare distributions. Fiddes and Turnoff Creeks are the smallest tributaries surveyed, and both tributaries have fairly active beaver populations. We compared the location of beaver dams to the upstream boundaries of redd distributions in Fiddes and Turnoff Creeks, but found redds located above beaver dams in both tributaries. Water levels were considerably lower in 2017, and the change in redd distribution may be related to lower flows making upstream passage more difficult for Bull Trout. Lower water levels in these smaller tributaries may increase the predation risk and some of the larger fish may have opted to spawn elsewhere. For example, we observed more redds in the Upper Halfway River in 2017 (75 redds) than in 2016 (20 redds).

5.2 Redd Abundance

Observer efficiency is a key parameter when calculating AUC abundance estimates. We calculated OE for both ground and aerial survey data. Ground OE was consistently higher in all the tributaries, while aerial OE was much lower and varied among surveys in all tributaries. Aerial OE was similar between the Chowade River (0.26) and Cypress Creek (0.28). In 2016, we did not have a large enough sample size of redds in the ground survey to calculate an OE for Cypress Creek. Instead, we used the value from the Chowade River as a surrogate. Similar aerial OE between the two tributaries in 2017 suggest that our assumption to use the Chowade River OE as a surrogate in 2016 may have been appropriate. Aerial OE was relatively similar in the Chowade River in 2016 (0.33) and 2017 (0.26).

Aerial OE decreased considerably in the Upper Halfway River from 2016 to 2017 (i.e., 0.79 to 0.37). The difference in aerial OE may be related to the small sample size of redds in the Upper Halfway River ground survey reach in both years, but particularly in 2016 when only nine redds were marked. When fewer redds are marked, highly observable clusters of redds may have a greater influence on the final OE. Also, the change in aerial OE may reflect variations in survey conditions such as water depth and clarity between the two years, or differences in helicopter survey conditions (e.g., glare, survey height, and survey speed). The high within-tributary variability in aerial OE contributed substantially to the overall uncertainty in the GAUC estimates. Additional data will inform the range in aerial OE for all tributaries, particularly those with smaller redd sample sizes, and can be used to improve the precision of GAUC estimates from previous years.

Survey life provides information on the degree of double counting across visual surveys (i.e., the same redd is counted during successive surveys). Field observations in 2016 and 2017 and linear mixed effects modelling suggest that SL in the Halfway Watershed may be variable among years, tributaries, and within tributaries. With only two years of redd abundance and SL data, we cannot determine whether SL is more accurate in one year *versus* the other. Flow conditions in 2016 were the highest in 40 years and the survey life was 10 days shorter in 2016 relative to 2017. Higher water levels and discharge would increase the concentration of suspended solids, increased particulate and periphyton drift and movement of substrate in the river, which would likely reduce the survey life of Bull Trout redds. Also, the number of redd surveys and the duration of the survey period both increased in 2017, which may have affected the survey life. Although the linear model accounts for the time before and after the survey period, additional information (i.e., a longer survey period) improves the accuracy of estimated SL. Additional years of SL data will inform how year, tributary, and water condition affect SL in the Halfway Watershed.

The Chowade River trail camera agreed with the SL estimate derived from linear modeling. We first observed the redd as age-1 on [REDACTED] (once it had already been created) and extended digging behaviour by several Bull Trout maintained the redd at age-1 until [REDACTED] (12 days). Fish that guard and are active around the redd may prevent recolonization of periphyton. The redd was assessed as age-3 when the tag was removed on Survey 4 (27 days after tagging), indicating that the total SL was longer than one month. Overall, the pilot trail camera program provided valuable insight into redd age and fish behaviour, but we were only able to successfully monitor one redd in one of the tributaries. Additional cameras will be deployed in 2018 to further reduce the uncertainty in SL and provide more accurate estimates of redd abundance.

GAUC estimates for the Chowade River and Cypress Creek were similar between 2016 and 2017 despite differences in redd distribution. The GAUC estimates for Fiddes and Turnoff Creeks were almost half of the estimate from 2016, which agrees with field observations and count data in 2017. The Upper Halfway River estimate was nearly 4-fold higher in 2017 compared to 2016. The large increase in redds in the Upper Halfway River may be due to a redistribution of spawners between the two years (i.e., fewer redds in both Turnoff and Fiddes Creeks and more redds in the Upper Halfway River). Due to reduced water levels in 2017, fish may have not have moved into the smaller and shallower tributaries (Turnoff and Fiddes Creeks) due to limited access.

Peak redd count indices for 2016 and 2017 were generally within the range of the baseline indices from 2002 to 2012, and the rank order of tributaries from highest to lowest abundance were similar to previous years. The Chowade River has consistently had the highest peak redd count among all tributaries surveyed (i.e., 3 out of the 3 baseline years with 2 or more tributaries counted). Based on field observations, habitat complexity in the Chowade River is consistently the highest (i.e., high amounts of large wood debris, large deep pools, many side channels) of the tributaries surveyed, which is positively related to spawner density in salmon populations (Braun and Reynolds 2011).

A power analysis was completed during the development of Mon-1b that evaluated the number of survey years required to detect an annual decline in redd abundance (of 10% to 50%) using historic redd estimation methods (Ma et al., 2015). The power analysis found that high rates of process error (i.e., true variation in population size) in the Halfway Watershed limited the ability to detect a decline in redd abundance, and only a small increase in power occurred when sampling error was reduced to zero (Ma et al., 2015). Although the increase in power gained using the GUAC method (i.e., reducing sampling error) is relatively small, the GAUC method provides a more accurate, precise, and informative abundance estimate. The improvement in accuracy is particularly valuable considering the small population sizes in tributaries of the Halfway Watershed. A more robust estimate will improve the ability to detect a decline before the population reaches critically low levels. Also, GAUC parameters for migration timing, observer error, and survey life can be used to improve the utility of historic redd abundance estimates and enhance models estimating changes in Bull Trout redd abundance through time.

5.3 Redd Area, Fish Length and Fecundity

Redd abundance can be a reliable indicator of Bull Trout spawning abundance (Gallagher et al. 2007), however it may not be an accurate indicator of egg deposition and thus juvenile recruitment without additional information. We observed substantial variation in redd size both within and among tributaries. Redd size is strongly correlated with fish length (Riebe et al. 2014), and because of the strong length-fecundity relationships present in salmonids (Kindsvater et al. 2016), redd size should also be correlated with the number of eggs a female deposits. We applied these well-established relationships to calculate rough estimates of fecundity for spawning Bull Trout in three tributaries of the Halfway Watershed with adequate redd size data.

First, we estimated the mean fork length of Bull Trout using the relationship between fish length and redd area from Riebe et al. (2014). Using this relationship, we estimated the fork lengths of fish that excavated the redds that we measured and calculated the mean fork length for Fiddes Creek (452 mm), Cypress Creek (399 mm), Chowade River (455 mm) and the Upper Halfway River (520 mm), which were similar to adult sizes captured during the juvenile sampling program (Golder Associates Ltd. 2016) and observed crossing the resistivity counter in the Chowade River in 2016 (Braun et al. 2017). We then used the fork lengths to estimate the number of eggs per female using a Bull Trout length-fecundity relationship parameterized from data found in McPhail and Baxter (2016). Female Bull Trout had a mean egg number estimate of 1,805 eggs, 1,837 eggs, 1,237 eggs, and 2,601 eggs in Fiddes Creek, the Chowade River, Cypress Creek, and the Upper Halfway River, respectively. We acknowledge that the fecundity estimates presented herein are coarse calculations, however the dramatic variation in fecundity among females could lead to large variation in juvenile recruitment and population dynamics in future years. The error surrounding the unaccounted-for variation in egg number among females within and among tributaries is likely larger than any error in the abundance of redds.

6 References

Bates, D., Maechler, M., Bolker, B., and Walker, S. 2015. Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software, 67(1), 1-48. Doi:10.18637/jss.v067.i01.

Bivan, R., Keitt, T., and Rowlingson, B. 2017. Rdgal: Bindings for the Geospatial Data Abstraction Library. R package version 1.2-15. https://CRAN.R-Project.org/package=rgdal.

Bivand., R.S., Pebesma, E., and Gomez-Rubio, Virgilio. 2013. Applied spatial data analysis with R, Second edition. Springer, NY. http://www.asdar-book.org/

Braun, D.C., and Reynolds, J.D. 2011. Relationships between habitat characteristics and breeding population densities in sockeye salmon (*Oncorhynchus nerka*). Canadian Journal of Fisheries and Aquatic Sciences. 68: 758-767.

Braun, D.C., Harding, J., Wilson, L.J., Marin, C., Chung, M. 2017. Peace River Bull Trout Spawning Assessment – Bull Trout Redd Counts (Mon-1b, Task 2b). Report prepared for BC Hydro – Site C Clean Energy Project – Vancouver, BC. 28 pages + 3 appendices.

Bridge JS (2003) Rivers and floodplains: forms, processes, and sedimentary record. Blackwell, Malden, pp 491

Brundsdon, C., and Chen, H. 2014. GISTools: Some further GIS capabilities for R. R package version 0.7-4. https://CRAN.R-project.org/package=GISTools

Diversified Environmental Services and Mainstream Aquatics Ltd. 2013. Upper Halfway River Watershed Bull Trout Spawning Survey 2012. Prepared for BC Hydro. Report No. 10016.

Diversified Environmental Services and Mainstream Aquatics Ltd. 2011. Upper Halfway River Watershed Bull Trout Spawning Survey 2010. Prepared for BC Hydro. Report No. 10016.

Diversified Environmental Services and Mainstream Aquatics Ltd. 2009. Upper Halfway River Watershed Bull Trout Spawning Survey 2008. Prepared for BC Hydro. Report No. 08008.

Gallagher, S.P., and C.M. Gallagher. 2005. Discrimination of Chinook and coho salmon and steelhead redds and evaluation of the use of redd data for estimating escapement in several unregulated streams in northern California. North American Journal of Fisheries Management. 25: 284-300.

Gallagher, S., P.K. Hahn, and D.H. Johnson. 2007. Redd counts. Pages 197–234 in D. H. Johnson, B. M. Shrier, J. S. O'Neil, J. A. Knutzen, X. Augerot, T. A. O'Neil, and T. N. Pearsons, editors. Salmonid field protocols handbook: techniques for assessing status and trends in salmon and trout populations. American Fisheries Society, Bethesda, Maryland.

Grant, S., C.H., Kalyn, S.M., Mahoney, J.E., and J.A. Tadey. 2007. Coho (*Oncorhynchus kisutch*) and chum (*O. keta*) salmon visual enumeration surveys in twenty-six lower Fraser River area streams, 1999-2005. Canadian Technical Report of Fisheries and Aquatic Sciences 2964. Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, BC, Canada, 154.

Golder Associates Ltd. 2016. Site C reservoir Tributary Fish Population Indexing Survey (Mon-1b, Task 2c) – 2016 Investigations. Report prepared for BC Hydro, Vancouver, British Columbia. Golder Report No. 1650533: 28 pages + 3 appendices.

Hilborn, R., B.G. Bue, and S. Sharr. 1999. Estimating spawning escapements from periodic counts: a comparison of methods. Canadian Journal of Fisheries and Aquatic Sciences. 56: 888–896.

Holt, K.R. and S.P. Cox. 2008. Evaluation of visual survey methods for monitoring Pacific salmon (*Oncorhynchus spp.*) escapement in relation to conservation guidelines. Canadian Journal of Fisheries and Aquatic Sciences. 65: 212–226.

Kindsvater, H.K., Braun, D.C., Otto, S.P., and Reynolds, J.D. 2016. Cost of reproduction can explain the correlated evolution in semelparity and egg size: theory and a test with salmon. Ecology Letters. 19:687-696.

Ma, B.O., Parkinson, E., Olson, E., Pickard, D.C., Connors, B., Schwarz, C., and D. Marmorek. 2015. Site C Monitoring Plan Power Analysis. Final report. Prepared for BC Hydro by ESSA Technologies Ltd. 64 pp + appendices.

McPhail, J. D., and Baxter, J. S. 1996. A review of bull trout *(Salvelinus confluentus)* life-history and habitat use in relation to compensation and improvement opportunities. Fisheries Management Report No. 104, 35 p.

Melville, C., D. Ramos-Espinoza, D. Braun, and D.J.F. McCubbing. 2015. Lower Bridge River adult salmon and steelhead enumeration, 2014. Report prepared for St'át'imc Eco-Resources and BC Hydro. 80 p.

Millar, R.B., S. McKechnie, C.E. Jordan, and R. Hilborn. 2012. Simple estimators of salmonid escapement and its variance using a new area-under-the-curve method. Canadian Journal of Fisheries and Aquatic Sciences. 69: 1002–1015.

Muhlfeld, C.C., M.L. Taper, and D.F. Staples. 2006. Observer error structure in Bull Trout redd counts in Montana streams: implication for inference on true redd numbers. Transaction of the American Fisheries Society. 135: 643-654.

Platts, W.S. 1979. Relationships among stream order, fish populations, and aquatic geomorphology in an Idaho river drainage. Fisheries 4: 5–9.

R Core Team. 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rand, P.S., C.P. Kellopn, X. Augerot, and M. Goslin. 2007. Comparison of sockeye salmon (*Oncorhynchus nerka*) monitoring in the Fraser River Basin, British Columbia, Canada and Bristol Bay, Alaska, USA. North Pacific Anadromous Fish Commission. 4: 271–284.

Riebe, C.S., Sklar, L.S. Overstreet, B.T., and Wooster, J.K. 2014. Optimal reproduction in salmon spawning substrates linked to grain size and fish length. Water Resources Research. 50: 898-918.

R.L. & L. Environmental Servicies LTD. 1995. Fish migrations in the Chowade River, B.C. Fall 1994. Report prepared for Ministry of Environment, Lands and Parks, British Columbia: 34 pages + 4 appendices.

Trouton, N.D. 2004. An investigation into the factors influencing escapement estimation for Chinook salmon (*Oncorhynchus tshawytscha*) on the lower Shuswap River, British Columbia. Master of Science thesis.

7 Appendices

Appendix 1. Counts of spawning Bull Trout during ground and aerial surveys.

Tributary	Survey	Number of Bull Trout	
		Ground	Aerial
Chowade River	1	16	19
	2	28	48
	3	0	4
	4	0	0
Cypress Creek	1	NA	15
	2	1	4
	3	0	2
	4	0	0
Fiddes Creek	1	0	4
	2	1	2
	3	0	1
	4	0	0
Turnoff Creek	1	NA	5
	2	NA	0
	3	NA	0
	4	NA	0
Upper Halfway River	1	3	25
	2	13	11
	3	0	3
	4	0	2

Appendix 2. Sensitivity of GAUC estimates to the addition of zero counts before the first survey and after the last survey. Mean estimates and standard errors are presented.

	Abundance			
Tributary	**Zeros at start and end**	**Zero at end**	**Zero at start**	**No zeros**
Chowade River	320 (109)	322 (110)	320 (113)	322 (117)
Cypress Creek	90 (42)	91 (46)	91 (48)	93 (62)
Fiddes Creek	63 (18)	63 (18)	63 (19)	63 (19)
Turnoff Creek	18 (8)	22 (10)	18 (9)	36 (94)
Upper Halfway River	75 (18)	75 (18)	76 (18)	77 (17)

Appendix 3. Example photos from the Chowade River trail camera showing a redd progressing from age-1 to age-3.